

Durham Research Online

Deposited in DRO:

17 November 2017

Version of attached file:

Accepted Version

Peer-review status of attached file:

Peer-reviewed

Citation for published item:

Wilson, M. P. and Foulger, G. R. and Gluyas, J. G. and Davies, R. J. and Julian, B. R. (2017) 'HiQuake : The Human-Induced Earthquake Database.', *Seismological research letters.*, 88 (6). pp. 1560-1565.

Further information on publisher's website:

<https://doi.org/10.1785/0220170112>

Publisher's copyright statement:

Wilson, M. P., Foulger, G. R., Gluyas, J. G., Davies, R. J. Julian, B. R. HiQuake: The Human-Induced Earthquake Database. *Seismological Research Letters*, 88, 1560-1565, 2017 ©Seismological Society of America.

Additional information:

Use policy

The full-text may be used and/or reproduced, and given to third parties in any format or medium, without prior permission or charge, for personal research or study, educational, or not-for-profit purposes provided that:

- a full bibliographic reference is made to the original source
- a [link](#) is made to the metadata record in DRO
- the full-text is not changed in any way

The full-text must not be sold in any format or medium without the formal permission of the copyright holders.

Please consult the [full DRO policy](#) for further details.

HiQuake: The Human-Induced Earthquake Database

Wilson, M. P. ^{a*}, Foulger, G. R. ^a, Gluyas, J. G. ^a, Davies, R. J. ^b, & Julian, B. R. ^a

^a Department of Earth Sciences, Durham University, Science Labs, Durham, DH1 3LE, UK

^b School of Civil Engineering and Geosciences, Newcastle University, Newcastle upon Tyne, NE1 7RU, UK

* Corresponding author. *E-mail address:* miles.wilson@durham.ac.uk

Key words: Anthropogenic, Earthquakes, Induced, Seismicity

Abstract

HiQuake – The Human-Induced Earthquake Database is the most complete database of anthropogenic projects proposed, on scientific grounds, to have induced earthquake sequences. It is freely available to download at www.inducedearthquakes.org. At the time of writing *HiQuake* contains ~730 anthropogenic projects proposed to have induced earthquakes, as well as associated project-related and seismic data. The most commonly reported anthropogenic activities proposed to have induced earthquakes are mining and water-reservoir impoundment. In recent years the number of earthquake sequences proposed to have been induced by fluid-injection activities has grown. The most commonly reported maximum observed magnitude in an induced earthquake sequence is $3 \leq M_{MAX} < 4$. The largest earthquake in *HiQuake* proposed to have been induced had a magnitude of M_W 7.9 and occurred in China. Such large earthquakes release mostly stress of natural tectonic origin, but are conceivably triggered by small anthropogenic stress changes. The data in *HiQuake* are of variable quality because they are drawn from publications that span almost a century. We estimate under-reporting to be ~30% for $M \sim 4$ events, ~60% for $M \sim 3$ events and ~90% for $M \sim 2$ events. The degree of certitude that given earthquake sequences were anthropogenically induced is variable. *HiQuake* includes all earthquake sequences proposed on scientific grounds to have been human-induced without regard to the strength of the case made. *HiQuake* is offered freely as a resource to interested parties and judging the reliability of any particular case is the responsibility of

26 the database user. *HiQuake* will be routinely updated to correct errors, update existing entries and
27 add new entries. It has the potential to help improve our understanding of induced earthquakes and
28 to manage their impact on society.

29 **1. Introduction**

30 Induced earthquakes can pose a direct threat to infrastructure and human life, and fear of them
31 can impact project viability. Understanding and managing them is thus of economic and social
32 importance. Of particular interest is estimating the maximum possible magnitude earthquake that a
33 project may induce (*e.g.* McGarr et al., 2002; McGarr, 2014; van der Elst et al., 2016), since this
34 parameter is important for hazard assessment. In the last few years the study of induced earthquakes
35 has intensified, primarily because of the coincident increase in seismic rates and waste-fluid
36 disposal activities in the United States of America, as well as the expanding use of hydraulic
37 fracturing for shale gas and oil recovery (Ellsworth, 2013). Many cases of induced earthquakes have
38 been studied in detail and documented. The first documented case of induced seismicity related to
39 underground fluid injection occurred at the Rocky Mountain Arsenal, Denver, in the 1960s (Evans,
40 1966). These cases provide a large body of data that gives context to modern induced earthquake
41 sequences and can help improve understanding of the phenomenon.

42 In 2016 Nederlandse Aardolie Maatschappij BV (NAM), a Dutch oil and gas exploration and
43 production company, funded a team of researchers from Durham and Newcastle Universities,
44 United Kingdom, to conduct a full review of induced earthquakes. This review extended a study by
45 Davies et al. (2013) in which 198 cases of induced earthquake sequences were documented where
46 the largest event had a magnitude of $M \geq 1.0$. Until the present project, this was the best-known
47 publically available database of induced earthquakes, although other compilations focussing on
48 specific anthropogenic activities also exist (*e.g.* Gupta, 2002; Li et al., 2007; Suckale, 2009; Evans
49 et al., 2012). Extending the database by Davies et al. (2013) became a component of a project led by
50 NAM that aimed to estimate the maximum possible magnitude earthquake that might be induced in

51 the Groningen gas field, Netherlands, which NAM operates (NAM, 2016). Induced earthquakes
52 probably began to occur due to gas production in the late 1970s, with the first officially-registered
53 induced earthquake in 1986 (van der Voort and Vanclay, 2015). The Groningen gas field is one of
54 the largest gas fields in the world and is therefore of significant economic importance.
55 Consequently, gas production continues but to assist with mitigation measures for induced
56 earthquakes NAM have made financial commitments to researching induced seismicity.

57 The resulting database of the full review, the Human-Induced Earthquake Database (*HiQuake*),
58 was formally released January 26th 2017 via the website www.inducedearthquakes.org. It has
59 subsequently been maintained and updated and the plan is to continue this work for the foreseeable
60 future. *HiQuake* is currently the largest and most up-to-date freely-available database of projects
61 proposed to have induced earthquake sequences. This article formally documents *HiQuake*,
62 describes how it was developed, including policy decisions that had to be made, provides an
63 overview of its contents, and reports initial observations. A more extensive review of induced
64 earthquakes based on the knowledge gained while developing *HiQuake*, and including specific case
65 studies, is given by Foulger et al. (in press).

66 **2. Database Contents and Availability**

67 *HiQuake* was compiled from peer-reviewed published literature, industry reports, government
68 reports, academic presentations, media articles and personal communications. A thorough search for
69 projects proposed to have induced earthquakes was conducted using a variety of methods including
70 searching on-line databases for keywords, checking all relevant papers in the reference lists of
71 known papers, searching the proceedings of major conferences, searching for reports published on-
72 line and gathering personal communications. After approximately six person-months of work we
73 essentially ceased to find any additional historical examples and the database grew primarily by the
74 addition of contemporary cases.

75 As the database grew it became clear that the strength of the scientific case for induction varied
76 from extremely strong to extremely weak, with many projects in between. A decision had to be
77 made regarding how strong the case should be for inclusion in the database. Because of the
78 subjectivity of judging the plausibility of individual cases, and the inevitability that opinion among
79 researchers would vary widely, it was decided to include all cases without regard to plausibility.
80 The database thus lists all projects proposed on scientific grounds (not religious or moral) to have
81 induced earthquake sequences. Judgement regarding the strength of the case made for any particular
82 entry is the responsibility of the user.

83 Each entry in *HiQuake* corresponds to a single project or distinct phase of a project. Some
84 projects have been underway for many years and have probably induced tens of thousands of
85 earthquakes, for example geothermal operations at The Geysers field, California (Mossop and
86 Segall, 2004; Majer and Peterson, 2007). Other projects were completed in a few hours or days and
87 may have induced only a few earthquakes, for example hydraulic fracturing at Preese Hall, United
88 Kingdom, which was associated with 52 recorded earthquakes (Clarke et al., 2014). Regardless of
89 the total number of earthquakes reported, each project or distinct project phase corresponds to a
90 single entry in *HiQuake*. In some cases the type of anthropogenic activity proposed to have induced
91 earthquakes is uncertain. For example in some hydrocarbon reservoirs fluid extraction and injection
92 have occurred simultaneously for many years. Along with the project name, other data recorded in
93 *HiQuake* include project type, location, maximum observed magnitude earthquake (M_{MAX}), and
94 operational parameters. A full list of database columns is given in Table 1.

95 The quality of the data in *HiQuake* varies because the database includes earthquakes that
96 occurred up to ~150 years ago and draws from publications as far back as 1931. The completeness
97 of the record and the accuracy of the data are expected to be poorer for older cases. A variety of
98 magnitude types for M_{MAX} are given in *HiQuake* because seismological practice has changed
99 greatly with time. Magnitude types within the database include M_L (local magnitude), m_b (body-

100 wave magnitude), M_S (surface-wave magnitude), M_d (duration magnitude) and M_W (moment
101 magnitude). Where a magnitude type is not specified in the data source we use the notation M . If
102 M_W is provided, we preferentially cite this. Because magnitudes measured using different scales are
103 not necessarily equivalent, this factor should be borne in mind when testing for correlations
104 between earthquake magnitude and other parameters. Rendering all the magnitudes to a common
105 scale is a subject for future work.

106 *HiQuake* is freely available to all stakeholders including industrialists, engineers, scientists,
107 governments and the general public. It provides basic context that may help stakeholders understand
108 the significance of induced earthquakes in context with other industrial costs, hazards and benefits.
109 It can also be used for research, for example to study correlations between seismicity and
110 operational parameters. This may assist in the design of hazard assessment strategies for industrial
111 projects. *HiQuake* is available at www.inducedearthquakes.org in Microsoft Excel spreadsheet
112 format. This format was chosen because of the wide variety of numerical and text data within
113 *HiQuake* and because it is a format widely accessible to both scientists and non-scientists. Scientific
114 users may need to re-format the database for particular uses. Database updates will be made
115 routinely to add new information and correct errors. To facilitate this the authors would be grateful
116 for any feedback from users, which may be submitted via the web form at
117 www.inducedearthquakes.org/contribute or by contacting the authors directly.

118 3. Initial Observations

119 At the time of writing *HiQuake* contains ~730 anthropogenic projects or project phases
120 proposed to have induced earthquakes (Table 2). The project types that contribute the most cases to
121 *HiQuake* are mining (37%) and the impoundment of water behind dams (23%). Injection activities
122 such as hydraulic fracturing for shale gas or oil, waste-fluid disposal, geothermal re-injection and
123 secondary recovery for hydrocarbons, account for ~10-15% of cases. Less well-known proposed

124 seismogenic processes include the construction of skyscrapers, quarrying, groundwater extraction
125 and nuclear bomb testing.

126 In some cases there is ambiguity regarding the causative process because multiple seismogenic
127 activities may be underway simultaneously, for example fluid injection and extraction. In addition,
128 there is clearly under-reporting. This may result from induced earthquakes going unrecognised or
129 from lack of motivation where the induced seismicity is inconsequential to communities or
130 industrial activity. Examination of the fractal distribution of M_{MAX} earthquakes via a Gutenberg-
131 Richter plot shows linearity at the high-magnitude end only for earthquakes $> M 5$, which yield a b-
132 value of $\sim 0.65 \pm 0.15$ (95% confidence value) (Fig. 1). Extrapolation of the b-slope suggests that
133 under-reporting is $\sim 30\%$ for $M \sim 4$ events, $\sim 60\%$ for $M \sim 3$ events and $\sim 90\%$ for $M \sim 2$ events.

134 The earliest entry in *HiQuake*, from 1868, is coal mining near Maitland, Australia (Klose,
135 2007a; 2007b). Seismogenic projects are reported from ~ 70 countries (Fig. 2). The largest
136 contributing countries at the time of writing are the United States of America (182 cases) and China
137 (148 cases). This does not necessarily mean these countries host more seismogenic projects, but it
138 could simply be that reporting is more complete. Some anthropogenic activities that are proposed to
139 induce earthquakes, such as water-reservoir impoundment and mining, are more globally diffuse
140 than others. The fastest-growing anthropogenic activity proposed to induce earthquakes may be
141 fluid-injection (Fig. 3) as exemplified by the recent remarkable increase in induced seismicity in
142 Oklahoma (Keranen et al., 2014).

143 The most commonly reported M_{MAX} in an induced earthquake sequence is $3 \leq M_{MAX} < 4$ (Fig.
144 4). The largest earthquake reported to date to be induced by fluid injection is $M_W 5.8$ (the 2016
145 Pawnee, Oklahoma, earthquake; Yeck et al., 2016), by water-reservoir impoundment $M_W 7.9$ (the
146 2008 Wenchuan, China, earthquake; Ge et al., 2009), by hydrocarbon extraction $M 7.3$ (the 1976
147 Gazli, Uzbekistan earthquake; Mirzoev et al., 2009) and by groundwater extraction $M_W 7.8$ (the
148 2015 Gorkha, Nepal, earthquake; Kundu et al., 2015). A large majority of the stress released by

149 such large earthquakes was without doubt of natural origin and the question of whether or not the
150 event was induced relates to the initial trigger that caused fault slip to start. Large earthquakes
151 commonly comprise a sequence of sub-events, each of which is triggered by the previous sub-event,
152 so large earthquakes may result from the induction of a much smaller initial event. As mentioned
153 above, we did not judge the strength of cases made and include in *HiQuake* all those for which a
154 scientific case has been presented.

155 **4. Summary**

156 Durham and Newcastle Universities, under contract with Nederlandse Aardolie Maatschappij
157 BV, have constructed the most complete database of human-induced earthquakes (*HiQuake*)
158 currently available. It may be downloaded as a Microsoft Excel spreadsheet from
159 www.inducedearthquakes.org. At the time of writing *HiQuake* lists ~730 anthropogenic projects or
160 project phases proposed to have induced earthquake sequences, along with a suite of meta-data
161 accompanying each case. The most commonly reported seismogenic project types are mining and
162 water-reservoir impoundment. In recent years the number of earthquake sequences proposed to
163 have been induced by fluid-injection activities has grown. Reported maximum observed magnitudes
164 are most commonly $3 \leq M_{\text{MAX}} < 4$, but this range varies depending on project type. The largest
165 earthquake proposed to have been induced to date is the M_w 7.9 Wenchuan earthquake, China.
166 Extremely large earthquakes like this may be initially triggered by a small stress change brought
167 about by anthropogenic activities, but most of the stress released is of natural tectonic origin.
168 *HiQuake* is inhomogeneous because data are drawn from publications spanning almost a century
169 and the observational detail given and seismological practice have varied during this long time
170 span. Under-reporting is a problem and we estimate that it is ~30% for $M \sim 4$ events, ~60% for M
171 ~ 3 events and ~90% for $M \sim 2$ events. The degree of certitude that given earthquake sequences were
172 anthropogenically induced is also variable. *HiQuake* includes all earthquake sequences for which a
173 scientific case has been made for human induction and judging the reliability of each case is the

responsibility of the database user. The database will be updated routinely to correct errors, revise existing entries and add new entries. *HiQuake* is freely available to all and may be of interest to industrialists, engineers, scientists, governments and the general public. It may contribute to increasing understanding of the spatial and temporal occurrence of induced earthquakes, their causes and relationships to operational parameters, and thus contribute to increasing industrial safety.

5. Data and Resources

The Human-Induced Earthquake Database (*HiQuake*) is an open-access database available at www.inducedearthquakes.org. At the time of writing the most recent update to the database occurred 25th July 2017.

Acknowledgments

We are grateful to Nederlandse Aardolie Maatschappij BV (NAM) for financially supporting the development of *HiQuake*. We thank two anonymous reviewers for their comments which helped improve the original manuscript.

References

- Clarke, H., Eisner, L., Styles, P., and Turner, P. 2014. Felt seismicity associated with shale gas hydraulic fracturing: The first documented example in Europe. *Geophysical Research Letters*, 41(23), 8308-8314.
- Davies, R., Foulger, G., Bindley, A., and Styles, P. 2013. Induced seismicity and hydraulic fracturing for the recovery of hydrocarbons. *Marine and Petroleum Geology*, 45, 171-185.
- Ellsworth, W. L. 2013. Injection-induced earthquakes. *Science*, 341(6142), 1225942.
- Evans, D. M. 1966. The Denver area earthquakes and the Rocky Mountain Arsenal disposal well. *The Mountain Geologist*, 3.

197 Evans, K. F., Zappone, A., Kraft, T., Deichmann, N., and Moia, F. 2012. A survey of the induced
198 seismic responses to fluid injection in geothermal and CO2 reservoirs in Europe.
199 *Geothermics*, 41, 30-54.

200 Foulger, G. R., Wilson, M. P., Gluyas, J. G., Julian, B. R., and Davies, R. J. in press. A global
201 review of human-induced earthquakes, *Earth-Science Reviews*.

202 Ge, S., Liu, M., Lu, N., Godt, J. W., and Luo, G. 2009. Did the Zipingpu Reservoir trigger the 2008
203 Wenchuan earthquake?. *Geophysical research letters*, 36(20).

204 Gupta, H. K. 2002. A review of recent studies of triggered earthquakes by artificial water reservoirs
205 with special emphasis on earthquakes in Koyna, India. *Earth-Science Reviews*, 58(3), 279-
206 310.

207 Keranen, K. M., Weingarten, M., Abers, G. A., Bekins, B. A., and Ge, S. 2014. Sharp increase in
208 central Oklahoma seismicity since 2008 induced by massive wastewater injection. *Science*,
209 345(6195), 448-451.

210 Klose, C. D. 2007a. Geomechanical modeling of the nucleation process of Australia's 1989 M5.6
211 Newcastle earthquake. *Earth and Planetary Science Letters*, 256(3), 547-553.

212 Klose, C. D. 2007b. Mine water discharge and flooding: A cause of severe earthquakes. *Mine Water*
213 *and the Environment*, 26(3), 172-180.

214 Kundu, B., Vissa, N. K., and Gahalaut, V. K. 2015. Influence of anthropogenic groundwater
215 unloading in Indo-Gangetic plains on the 25 April 2015 Mw 7.8 Gorkha, Nepal earthquake.
216 *Geophysical Research Letters*, 42(24).

217 Li, T., Cai, M. F., and Cai, M. 2007. A review of mining-induced seismicity in China. *International*
218 *Journal of Rock Mechanics and Mining Sciences*, 44(8), 1149-1171.

219 Majer, E. L., and Peterson, J. E. 2007. The impact of injection on seismicity at The Geysers,
 220 California Geothermal Field. *International Journal of Rock Mechanics and Mining Sciences*,
 221 44(8), 1079-1090.

222 McGarr, A. 2014. Maximum magnitude earthquakes induced by fluid injection. *Journal of*
 223 *Geophysical Research: Solid Earth*, 119(2), 1008-1019.

224 McGarr, A., Simpson, D., and Seeber, L. 2002. Case histories of induced and triggered seismicity.
 225 *International Handbook of Earthquake and Engineering Seismology*, 81A, 647-661.

226 Mirzoev, K. M., Nikolaev, A. V., Lukk, A. A., and Yunga, S. L. 2009. Induced seismicity and the
 227 possibilities of controlled relaxation of tectonic stresses in the Earth's crust. *Izvestiya,*
 228 *Physics of the Solid Earth*, 45(10), 885.

229 Mossop, A. P., and Segall, P. 2004. Induced seismicity in geothermal fields II—Correlation and
 230 interpretation at The Geysers. *J. Geophys Res.*

231 Nederlandse Aardolie Maatschappij BV (NAM). 2016. Report on Mmax Expert Workshop.
 232 Groningen Seismic Hazard and Risk Assessment. 8-10 March 2016. World Trade Centre,
 233 Schiphol Airport, The Netherlands, 220-254.

234 Suckale, J. 2009. Induced seismicity in hydrocarbon fields. *Advances in geophysics*, 51, 55-106.

235 van der Elst, N. J., Page, M. T., Weiser, D. A., Goebel, T. H., and Hosseini, S. M. 2016. Induced
 236 earthquake magnitudes are as large as (statistically) expected. *Journal of Geophysical*
 237 *Research: Solid Earth*, 121(6), 4575-4590.

238 van der Voort, N., and Vanclay, F. 2015. Social impacts of earthquakes caused by gas extraction in
 239 the Province of Groningen, The Netherlands. *Environmental Impact Assessment Review*, 50,
 240 1-15.

241 Yeck, W. L., Hayes, G. P., McNamara, D. E., Rubinstein, J. L., Barnhart, W. D., Earle, P. S., and
242 Benz, H. M. 2017. Oklahoma experiences largest earthquake during ongoing regional
243 wastewater injection hazard mitigation efforts. *Geophysical Research Letters*, 44(2), 711-
244 717.

245

246

247

248

249

250

251

252

253

254

255

256

257

258

259

260

Column contents

Country
Earthquake cause (main class)
Earthquake cause (subclass)
Project name
Latitude
Longitude
Project start date
Project end date
Seismicity or monitoring start date
Seismicity of monitoring end date
Delay time
Number of recorded earthquakes
Maximum observed magnitude (M_{MAX})
Magnitude type
Depth of M_{MAX} (m)
Date of M_{MAX} (yyyy/mm/dd)
Year of M_{MAX}
Distance of M_{MAX} to project (m)
Maximum distance of earthquakes to project (m)
Lithology/Resource
Depth of most seismicity (m)
Depth of project (m)
Tectonic setting
Notable previous seismicity
Dam height (m)
Area (km^2)
Maximum injection/extraction rate
Units of injection/extraction rate
Total volume or mass of material injected/extracted
Units of total volume or mass of material injected/extracted
Maximum injection pressure (MPa)
Change in reservoir pressure (MPa)
Stress change (MPa)
Bottom hole temperature ($^{\circ}\text{C}$)
Notes
Reference(s)

262

263

264

265

266 **Table 2**

Anthropogenic activity	Number of reported cases	Percentage of database to nearest integer (%)
Carbon Capture and Storage (CCS)	2	0
Construction	2	0
Conventional oil and gas	107	15
Deep Penetrating Bombs	4	1
Hydraulic fracturing for shale gas or oil	29	4
Geothermal	57	8
Groundwater extraction	5	1
Mining	271	37
Nuclear explosions	22	3
Research experiments	14	2
Unspecified oil & gas extraction; waste fluid disposal	12	2
Waste fluid disposal	36	5
Water reservoir impoundment	167	23
Total	728	

267

268

269

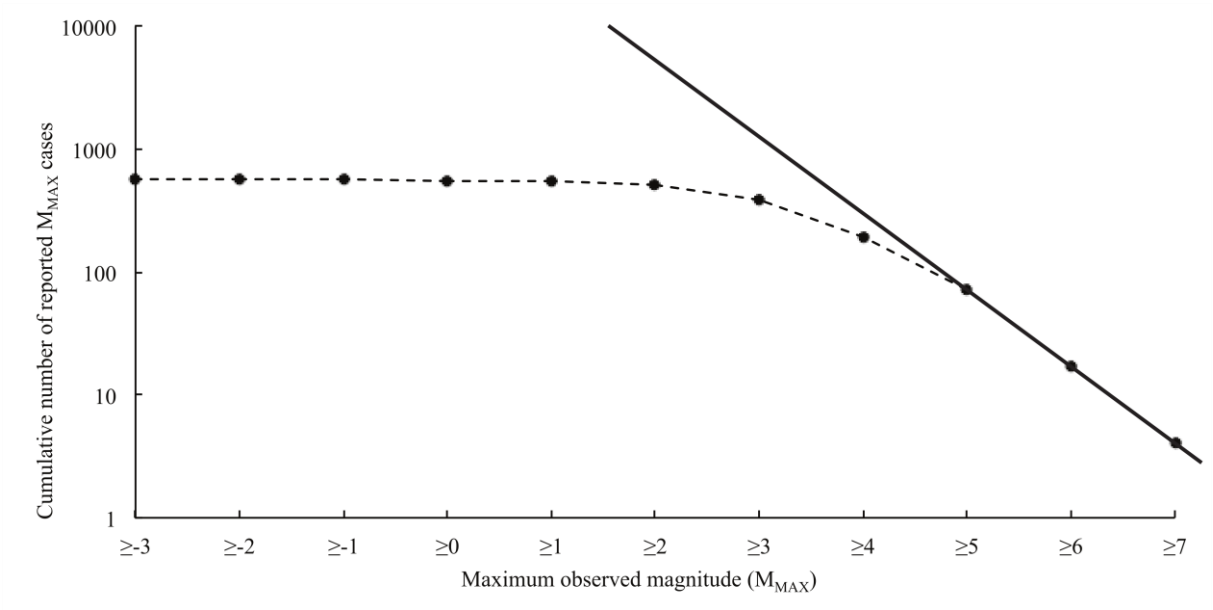
270

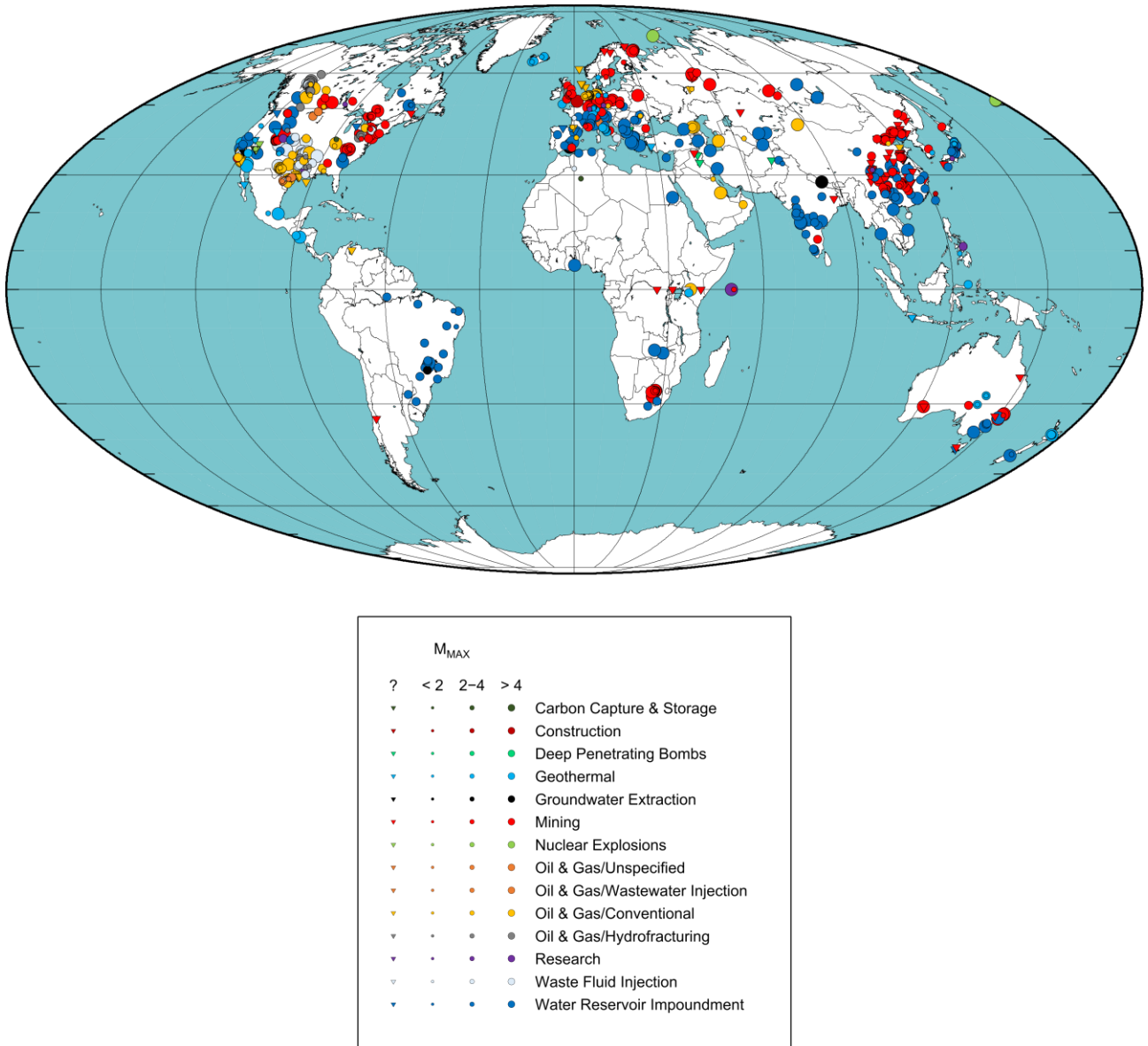
271

272

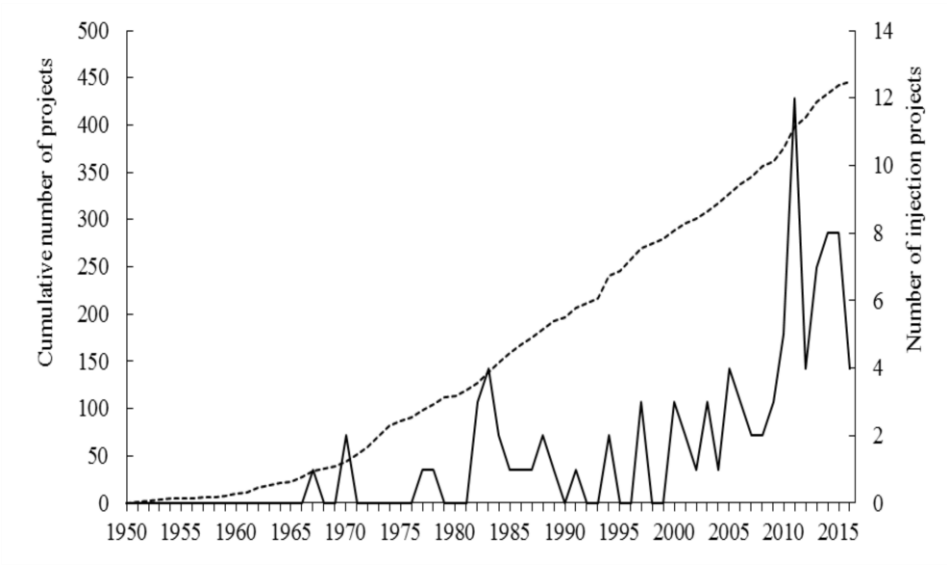
273

274 **Figure 1**

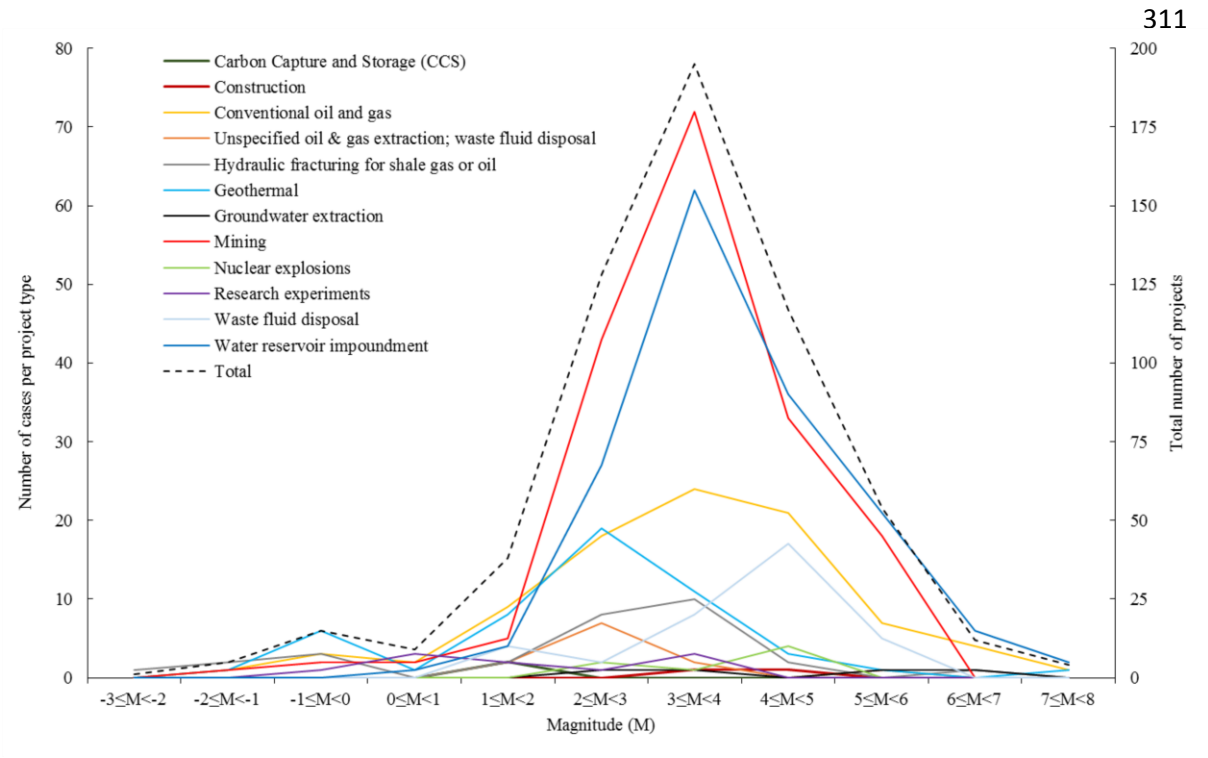




296 **Figure 3**



310 **Figure 4**



319

320

321

322

323

324

325

326

327

328

329 **Table captions**

330 Table 1: List of column names within *HiQuake*.

331 Table 2: The numbers of each type of anthropogenic activity proposed to have induced earthquakes.

332 Data from *HiQuake*.

333

334

335

336

337

338

339

340

341

342

343

344

345

346

347

348

349 **Figure captions**

350 Figure 1: Gutenberg-Richter plot with b-slope of M_{MAX} earthquakes within *HiQuake*.

351 Figure 2: World map showing the location of projects proposed to have induced seismicity. Data
352 from *HiQuake*.

353 Figure 3: Number of projects with reported M_{MAX} earthquakes and year of M_{MAX} since 1950.

354 Dashed line is the cumulative number of all anthropogenic projects and the solid line is the annual
355 number of injection projects. Data from *HiQuake*.

356 Figure 4: Number of cases vs. M_{MAX} for projects where M_{MAX} is provided. Data from *HiQuake*.